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The Supercritical Pile GRB Model: The Prompt to Afterglow Evolution

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ABSTRACT

The "Supercritical Pile" is a very economical GRB model that provides for the efficient conversion of the energy stored in the protons of a Relativistic Blast Wave (RBW) into radiation and at the same time produces - in the prompt GRB phase, even in the absence of any particle acceleration - a spectral peak at energy ~ 1 MeV. We extend this model to include the evolution of the RBW Lorentz factor Γ and thus follow its spectral and temporal features into the early GRB afterglow stage. One of the novel features of the present treatment is the inclusion of the feedback of the GRB produced radiation on the evolution of Γ with radius. This feedback and the presence of kinematic and dynamic thresholds in the model are sources of potentially very rich time evolution which we have began to explore. In particular, one can this way obtain afterglow light curves with steep decays followed by the more conventional flatter afterglow slopes, while at the same time preserving the desirable features of the model, i.e. the well defined relativistic electron source and radiative processes that produce the proper peak in the νF_ν spectra. In this note we present the results of a specific set of parameters of this model with emphasis on the multiwavelength prompt emission and transition to the early afterglow.

Subject headings: Gamma Rays: Bursts

1. Introduction

The cosmological origin of GRB has by now been firmly established following the discovery of their afterglows and the determination of their redshifts (Costa et al. 1997; van Paradijs, et al. 1997) and the launch of *Swift* which increased the number of observed afterglows and redshift determinations. These developments left little doubt that GRB emission is intimately associated with Relativistic Blast Waves (RBW), as proposed by Rees & Mészáros (1992) and at the same time shifted the focus of the study from the prompt GRB emission to its afterglow (Zhang & Mészáros 2004; Piran 2004).

The early, sparsely sampled GRB afterglow light curves, were fit well with simple power law functions, appropriate to emission from either spherical (Sari, Piran, & Narayan 1998) or jet-like (Sari, Piran & Halpern 1999) RBW. However, the launch of *Swift* with its prompt, continuous, broad frequency coverage has provided new unexpected (and unexplained) details of the afterglow light curves. Chief amongst them are: (a) An early afterglow steep decrease of the flux ($\propto t^{-3}$ to t^{-6}) followed often by a period of constant flux (before its eventual power law decline) in many bursts. (b) Large flares in the X-ray light curves $\sim 10^3 - 10^5$ sec after the beginning of the event (see O'Brien et al. 2006, for more details). These were compounded to the already open problems of the prompt emission, namely: (c) The GRB "inner engine". (d) The non-dissipative transport of the GRB energy to the emission region and, most importantly, its efficient dissipation there. (e) The physics behind the characteristic energy of peak GRB emission, $E_{\rm p}$ and its narrow distribution within the class of the classic GRB (Mallozzi et al. 1995; Preece et al. 2000). (f) The physics that relate GRB to XRR (X-Ray Rich bursts) and XRF (X-Ray Flashes), transients of lower flux and lower $E_{\rm p}$, recorded by broad band missions such as *BeppoSAX*, *HETE* and *Swift* (e.g Yonetoku et al. 2004).

Of the above problems, (a) has received no apparent resolution while (b) is loosely attributed to continued activity at the "inner engine"; while not implausible, this demands activity over time scales almost 10^7 times longer than the characteristic time associated with the "inner engine" dynamics ($\simeq 10^{-3}$ sec), as the latter is thought related to stellar collapse. (d) is considered to be effected either through protons (e.g Rees & Mészáros 1992) or magnetic fields (Vlahakis & Königl 2001), however, the necessary and efficient dissipation "is one of the least studied aspects of GRB" (Piran 2004); this issue is generally approached by parameterizing the energy density in relativistic electrons to be a given fraction (typically $\sim 50\%$) of that of protons. Issue (e) is generally open, given the absence of an underlying reason for such a characteristic energy. Monte Carlo simulations of a large number of models (Zhang & Mészáros 2003) failed to reproduce the narrow width of the observed distribution because of the large number of parameters involved and/or because of the lack of strong dependence of $E_{\rm p}$ on any single parameter. Finally, there are a number of

proposals concerning (f) (Yamazaki, Ioka & Nakamura 2002; Dermer, Chiang, & Böttcher 1999), which appear plausible but without a single one of them universally agreed upon.

The "Supercritical Pile" Model (SPM) (Kazanas, Georganopoulos & Mastichiadis 2002; Mastichiadis & Kazanas 2006, henceforth KGM02 and MK06), adapted from AGN (Kazanas & Mastichiad 1999), has been introduced to provide a resolution to (d). The compelling arguments in favor of the SPM are: (1) *Its economic* (non-thermal particles not necessary), *efficient conversion of the RBW relativistic proton energy into photons* through a radiative instability akin to that of a supercritical nuclear pile. (2) *Its spectra which exhibit a characteristic value for* $E_{\rm p} \simeq 1$ MeV (in the lab frame) irrespective of the RBW Lorentz factor Γ, in agreement with observation (Mallozzi et al. 1995), *produced as "unintended consequence" of the dissipation process.* Crucial in addressing these issues has been the presence of an upstream medium which scatters the RBW photons (a "mirror") and allows them to be re-intercepted by the RBW, while boosted in energy by $\simeq \Gamma^2$.

In MK06 we have explored numerically the SPM assuming a constant Lorentz factor Γ for the RBW, confirmed the efficiency of proton energy conversion into to radiation and the presence of a well defined value for $E_{\rm p}$, reflecting the kinematic threshold of the reaction $p\gamma \rightarrow p\, e^+e^-$. The present treatment is far more realistic: (a) It computes the evolution of the RBW Lorentz factor Γ through a medium of density $n(r) \propto R^{-2}$, thought to represent the wind of a WR star, including also the effects of the radiative drag of the bulk-Comptonized photons. (b) Replaces the upstream "mirror" required by the model by scattering the RBW photons in this medium. The combination of these effects can result in a rich GRB time evolution, but we presently restrict ourselves to a specific example of a GRB light curve, deferring the broader exploration of other models to a future publication. Despite this limited scope, we can reproduce some of the salient features of the GRB in the afterglow evolution, such as their steep decrease in flux following the termination of their prompt phase, an effect traceable in this specific case to the kinematic threshold of the model.

In §2 we provide the general framework of our model with emphasis on its novel aspects compared to previous treatments. In §3 we present the results of our calculations and finally in §4 the results are summarized and conclusions are drawn.

2. The Coupled Radiative – Dynamical Evolution

We consider a Relativistic Blast Wave (RBW) of speed $\upsilon_0 = \beta_\Gamma c$ and Lorentz factor Γ. Its radius $R(t)$ is measured from the center of the original explosion and it is sweeping up the CircumStellar Medium (CSM) of density $\rho_{\rm CSM}$. The evolution of Γ as a function of

radius is given by the combination of the conservation laws of mass

$$\frac{dM}{dR} = 4\pi R^2 \Gamma \rho_{\rm CSM} - \frac{1}{c^3\Gamma}\dot{E} \tag{1}$$

and energy-momentum

$$\frac{d\Gamma}{dR} = -\frac{4\pi R^2 \rho_{\rm CSM}\Gamma^2}{M} - \frac{F_{\rm rad}}{Mc^2}. \tag{2}$$

(Chiang & Dermer 1999). Here $\dot{E}$ is the radiation emission rate as measured in the comoving frame and $F_{\rm rad}$ is the radiation drag force exerted on the RBW by any radiation field exterior to the flow. Given that the RBW velocity v_0 is very close to the speed of light c, the entire radiative history of the RBW lies just ahead of it at a distance $D \sim R/\Gamma^2$; therefore, isotropization of this radiation by scattering in the ambient medium (the action of the "mirror") will lead to its re-interception by the RBW to thus contribute to $F_{\rm rad}$. This is given by the expression

$$F_{\rm rad} = \frac{64\pi}{9c}\tau_b n_e^{CSM}\sigma_T R\Gamma^4\dot{E} \tag{3}$$

where τ_b is the RBW Thomson depth, $n_e^{CSM} = \rho_{\rm CSM}/m_H$ the CSM electron density and σ_T the Thomson cross section. In the above expression, two powers of Γ are due to the increase of the photon energy density upon its scattering on the "mirror" while the other two to the usual radiative loss rate (an analogous term due to the $p\gamma \rightarrow pe^+e^-$ reaction was found to increase $F_{\rm rad}$ by 20% for the specific parameter values discussed herein but it maybe more important for different values). The calculation of the $\dot{E}$ and F_{rad} terms is done by implementing the numerical code used in MK06 to compute the radiation of the SPM. This is done be solving the simultaneous equations

$$\frac{\partial n_i}{\partial t} + L_i + Q_i = 0. \tag{4}$$

The unknown functions n_i are the differential number densities of protons, electrons and photons while the index i can be any one of the subscripts 'p', 'e' or 'γ' referring to each species. The operators L_i denote losses or escape of each species from the system while Q_i denote injection and source terms of each species by each of a number of processes which are described in detail in MK06. The above equations are solved in the fluid frame in a spherical volume of radius $R_b = R/\Gamma$. This can be justified by the fact that due to relativistic beaming an observer receives the radiation coming mainly from a small section of the RBW of lateral width R/Γ and longitudinal width R/Γ^2 in the lab but R/Γ on the comoving frame.

The present treatment differs from that of MK06 in two important aspects:

(1) Hot protons accumulate continuously on the RBW as it sweeps the CSM. This then sets the source terms of the protons ($Q_p^{\rm inj}$) and electrons ($Q_e^{\rm inj}$) (with units parti-

cles/energy/volume/time) to

$$Q_p^{\rm inj} = \frac{\rho_{\rm CSM} c}{m_p^2 c^2 R}(\Gamma^2 - \Gamma)\delta(\gamma_p - \Gamma) \tag{5}$$

and

$$Q_e^{\rm inj} = \frac{\rho_{\rm CSM} c}{m_p m_e c^2 R}(\Gamma^2 - \Gamma)\delta(\gamma_e - \Gamma) \tag{6}$$

i.e. we assume that at each radius R the RBW picks up an equal amount of electrons and protons from the circumstellar medium which have, upon injection, energies $E_p = \Gamma m_p c^2$ and $E_e = \Gamma m_e c^2$ respectively. Consequently, the proton *energy* injection rate is given by (Blandford & McKee 1976)

$$\left(\frac{dE}{dt}\right)_{\rm inj} = 4\pi R^2 \rho_{\rm CSM}(\Gamma^2 - \Gamma)c^3 \tag{7}$$

while a fraction m_e/m_p of the above goes to electrons.

(2) The scattering of the RBW photons takes place on the CSM ahead of the advancing RBW (rather than an *ad hoc* mirror) and, as such, its photon scattering column is uniquely determined by the initial conditions and, like all other parameters is a function of time (or equivalently position).

Eqns. (1), (2), (4), along with Eqns. (3), (5) and (6) form a set which can be solved to yield simultaneously the evolution of the RBW dynamics and luminosity. This approach is self-consistent in that the 'hot' mass injected through equations (5) and (6) shows up at RHS of Eqn. (1), while the radiated luminosity $\dot{E}$ feedbacks onto the energy-momentum equation through the definition of the radiative force, $F_{\rm rad}$, of Eqn. (3). The free parameters of this system are (i) the total energy of the explosion $E_{\rm tot}$ (ii) the CSM density profile $n(r)$ (iii) the magnetic field as a function of radius $B(r)$. To avoid computation of the evolution during the RBW acceleration phase when it likely produces little radiation, we have chosen to begin our calculations (and the accumulation of matter by the RBW) at a radius R_0 at which is has already achieved its asymptotic Lorentz factor $\Gamma_0 = \Gamma(R_0)$.

As proposed in KGM02 and shown explicitly in MK06, the relativistic protons accumulated in the RBW can become supercritical to the network of $p\gamma \rightarrow p\, e^+e^-,\ eB \rightarrow \gamma$ once kinematic and dynamic thresholds are simultaneously fulfilled. The kinematic threshold simply reflects the kinematic threshold of the $p\gamma \rightarrow p\, e^+e^-$ reaction and reads

$$b\,\Gamma^5 \gtrsim 1 \quad \text{or} \quad \Gamma \gtrsim 214\ (n_0)^{-1/12} \quad \text{for} \quad B = B_{eq} \simeq (8\pi m_p c^2 n_0)^{1/2}\Gamma \tag{8}$$

with the latter expression for B-field in equipartition, where $b = B/B_{crit}$ and $B_{crit} = m^2c^3/e\hbar$ is the critical magnetic field. The dynamic threshold provides the critical column density

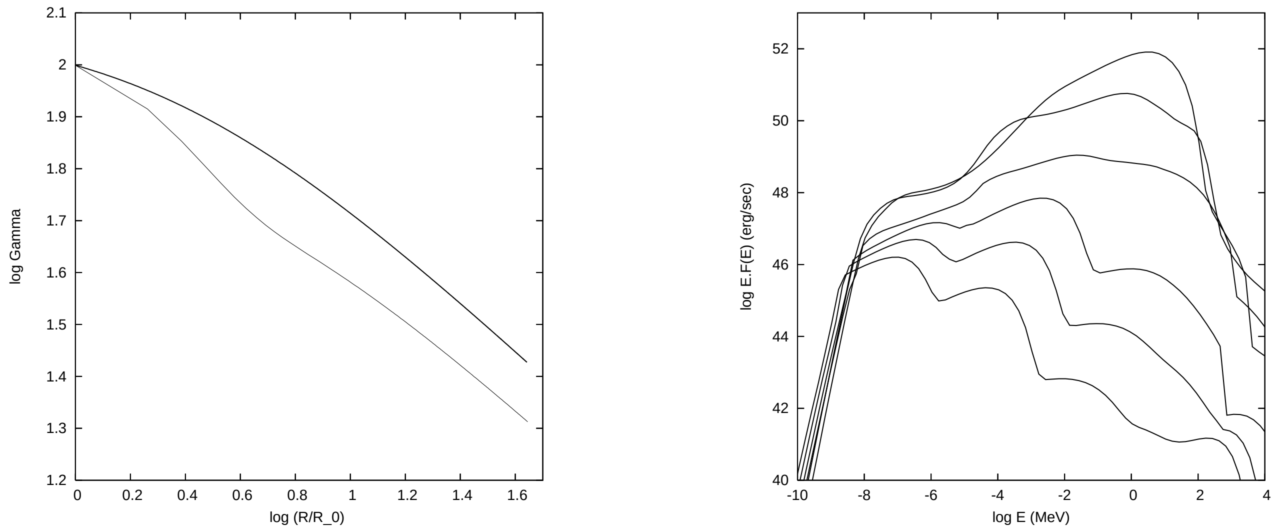

Fig. 1.— (a) The Lorentz factor for a RBW propagating in a wind environment with parameters given in the text. The thick lines show the evolution with radius without radiative drag, while the thin one with the drag included. (b) The multiwavelength spectrum of the burst at times 1, 3, 10, 30, 100 and 300 sec (top to bottom). The peak of the bulk Comptonized component is originally close to 1 MeV, however, as the evolution proceeds it moves to lower energies.

for the accumulated relativistic protons to become supercritical (in a fashion analogous to a nuclear pile) and, if fulfilled, a large fraction of the energy stored in relativistic protons is converted into e^+e^--pairs within a few light travel times across the width of the shock.

At the earliest stages of the RBW evolution the accumulated relativistic proton column is small and little emission is possible, only that of the swept-up electrons, which is smaller than the energy flux through the shock by a factor m_e/m_p and may very well represent the oft quoted GRB precursor emission. The eventual evolution of the RBW depends on whether its asymptotic Lorentz factor Γ_0 and $B-$field satisfy the kinematic threshold (Eqn. 8). If not, and in the absence of an accelerated population of particles, only the energy flux in electrons is converted to radiation and the GRB is a "dud", as the combination $b\,\Gamma^5$ is only expected to decrease with radius (however an explosive release is still possible if the proton distribution includes an accelerated power law component that extends to $E \gg \Gamma m_p c^2$; as hinted in Kazanas, Mastichiadis & Georganopoulos (2006), these events may be related to the XRRs and XRFs).

Far more interesting is the case where the kinematical criterion is satisfied initially. Then whether the flow becomes radiatively unstable depends on the column of hot protons accumulated on the RBW. When this exceeds the critical value, the energy contained in relativistic protons is explosively released, the value of $F_{\rm rad}$ increases dramatically and the Lorentz factor Γ of the RBW can decrease over a distance $D \ll R(t)$, provided that the

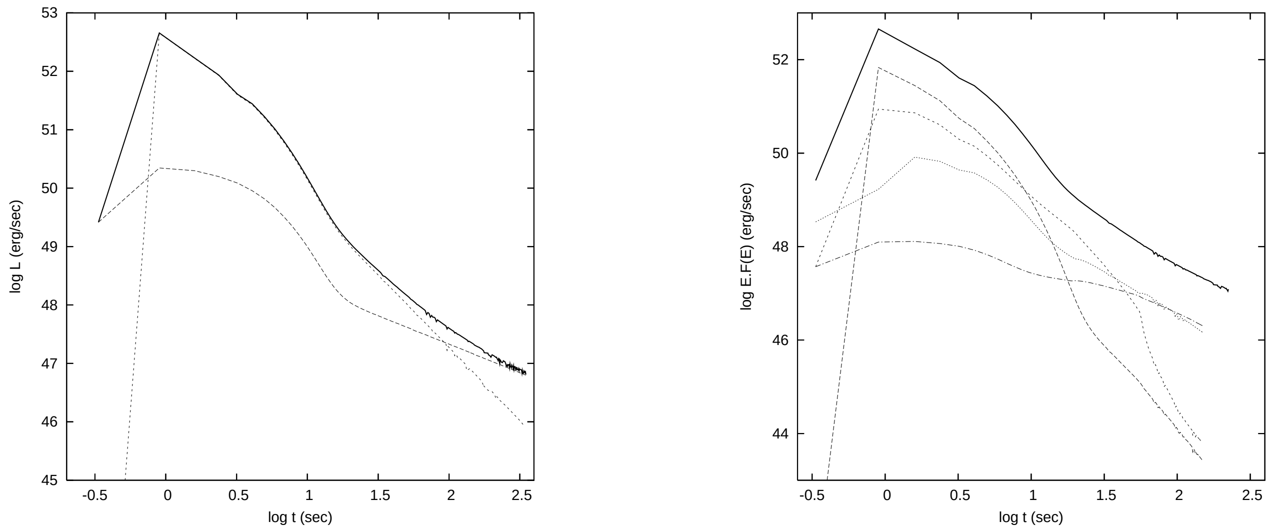

Fig. 2.— (a) The bolometric burst lightcurve. The dashed line corresponds to the internal RBW luminosity while the dotted line is the bulk Comptonized component. The thick line is the sum of the two. (b) The corresponding burst luminosity for various energy bands as a function of time. Long dashed line is at energy of 1 MeV, short dashed is at 10 keV, dotted at 100 eV and dot-dashed at 1 eV. The thick full line is the bolometric lightcurve. Parameters are as given in the text.

second term in Eq. (2) is dominant. This drop in Γ is important not only for decreasing the emitted flux but, more significantly, for potentially pushing $b\,\Gamma^5$ below its kinematic threshold value $\simeq 1$, (as is the case shown in Fig. 1a), a fact that according to the SPM marks the end of the prompt GRB emission phase, i.e. the conversion of proton energy into radiation. Following this event, radiation is emitted only from cooling the electrons already present within the RBW and those being swept-up by it. The observed flux suffers a precipitous decrease with further evolution that depends on the value of R relative to the deceleration radius $R_{\rm dec}$ corresponding to the resulting value of Γ; if $R < R_{\rm dec}$, the flux remains at a roughly constant level until Γ resumes its decline, at $R > R_{\rm dec}$, through accumulation of mass on the expanding RBW; if $R > R_{\rm dec}$, then Γ will continue its decline at the much slower conventional level of afterglow theory.

The detailed, long term evolution of the GRB flux depends on $E_{\rm tot}$, $n(r)$ and $B(r)$ that determine the values of r and Γ at which the RBW becomes supercritical – it is conceivable that for certain parameter combinations supercriticality can be reached at more than one radius, with the released energy being proportional to the time between the corresponding bursts see e.g. Ramirez-Ruiz & Merloni (2001). In Figure 1 and 2 we present the evolution of a RBW with $n = n_0(R_0/R)^2$ and $B = B_0(R_0/R)$. The parameters are $R_0 = 10^{14}$ cm, $n_0 = 8.10^8$ cm^{-3}, $\Gamma_0 = 100$, $B_0 = 4.4\ 10^4$ G and total isotropic energy $E_{\rm tot} = 10^{54}$ erg.

Figure 1a depicts the evolution of Γ as a function of radius in this medium with (thin

line) and without (thick line) the radiative feedback. The drop in Γ corresponds to the explosive energy release in the protons and the slow down of the RBW due to the radiation drag. As deduced from this figure, $R_0 \simeq R_{\rm dec}$, since for $R > R_0$, $\Gamma \propto R^{-1/2}$, as expected for adiabatic propagation in a wind density profile (thick line). After the decrease in Γ due to the radiative feedback and after the non-adiabatic effects have died out, the evolution of Γ follows a similar track of lower normalization.

Figure 1b shows the multiwavelength spectra at various instances as perceived by the observer. As it was shown in MK06 the spectrum consists of two components, one that is due to the primary particle emission by particles on the RBW and one due to the bulk Comptonization of the upstream-reflected primary radiation by the cold pairs of the RBW. This latter component peaks early on at 1MeV, but as the burst evolves moves to lower energies since both Γ and B drop outward.

Figure 2a shows the corresponding apparent isotropic bolometric luminosity as a function of time. This consists of the internally produced luminosity (dashed) and that due to bulk Comptonization of the mirror-scattered radiation by the RBW (dotted) with the thick line representing their sum. As it can also be seen from Fig 1b, most of the luminosity, is by far contained in the bulk-Comptonized component (at $E \sim 1$ MeV) and exhibits the steepest decrease due to the decrease in Γ and the arrest of additional pair injection from the protons. At longer time scales, the only injection available is that of the ambient electrons and the emission exhibits the $\propto t^{-1}$ behavior of "standard" afterglows.

Finally Fig. 2b depicts the luminosity at various energy bands as a function of time – here we make no distinction between the direct and the bulk Comptonized component, but instead we exhibit their sum. As a rule higher frequencies dominate more at the early stages of the burst but drop faster due to a combination of faster cooling and the decrease in Γ. This is consistent with observations: the BAT flux (that receives its major contribution from the bulk Comptonized component) decreases much faster than the flux in the other bands and its level defines, in effect, the prompt GRB phase (see also next section).

3. Summary, Discussion

We have presented above a first attempt at an integrated version of the SPM, complete with the coupled RBW dynamics, radiation production and accumulation of hot protons on the RBW from the swept-up matter. The latter process is fundamental as the increase of the hot proton column to supercritical values is necessary for the explosive energy release seen in GRB. Another important feature is the coupling of the radiation to the dynamics of

the RBW, the cause of the abrupt decrease in Γ seen in Fig. 1a. Because this can reduce Γ below the SPM kinematic threshold, it can severely reduce the observed flux, especially its bulk-Comptonized spectral component that peaks at $E_p \simeq 1$ MeV and constitutes the main GRB channel. The existence of the kinematic threshold value for Γ and its intimate association to the radiation emission near E_p (~ 1 MeV, the defining GRB property), affords for the SPM an operational definition of the GRB prompt phase, a feature unique amongst GRB models: as such, *the prompt GRB phase is the stage in its evolution during which the kinematic threshold condition of Eq. (8) is fulfilled*, accompanied by severe reduction in the GRB flux following this stage, as observed.

The time evolution of the flux in Fig. 2 bears great resemblance to that of many *Swift-XRT* GRB, that exibit a very steep declining profile followed by a less steep or flat section in their light curves (O'Brien et al. 2006), related, as discussed above, to the relation between R_0 and $R_{\rm dec}$. We believe that the straightforward way that the SPM addresses these vexing for the standard model questions attests to its relevance to the GRB underlying physics and phenomenology. It should be noted at this point that the efficiency of conversion of kinetic energy to radiation depends on the value of the ambient density n_0. This dependence comes through the dynamic threshold of the SPM, as n_0 determines also the value of the upstream albedo (i.e. of the "mirror", whose assumption is now obviated), to which the dynamic threshold is proportional. We plan to explore the effects of this parameter on the GRB properties in a future publication.

The duration of the burst shown in Fig. 2 is of order of a few seconds. As such it would be classified as a short burst, despite the fact that the RBW is assumed to propagate in a medium with properties akin to the wind of a WR star. We therefore have presented an explicit model that produces a short burst from an object of a young stellar population. While it was originally proposed and supported by the earlier observations that short bursts are associated with old stellar populations (implying neutron star collisions as their source of energy), it was shown (Berger, 2008) that $\lesssim 1/3$ of them are in fact associated with stellar populations similar to those of the long GRBs.

The outlook from this first time-dependent treatment of the SPM replete with the CSM distribution and radiation emission and feedback is that this model can potentially produce a great variety of GRB light curves (in agreement with GRB phenomenology) which it can relate to *global* parameters of the system. We plan to explore thoroughly these parameters in future publications.

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